RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 39, NUMBER 4 APRIL 1989

Single-particle strength distributions in ^{41}Ca

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(Received 13 June 1988)

Neutron strength distributions of ^{41}Ca have been obtained from a high-resolution study of the ^{40}Ca$(\vec{d},p)$ reaction. They agree well with quasiparticle-phonon coupling calculations in a large configuration space including major shell mixing. We see no evidence of strong depopulation of closed-shell orbitals.

Recently the validity of the independent-particle model of nuclei has been discussed with interest. In closed-shell nuclei deviations have been interpreted as being due to long-range correlations of the phonon or pairing type, which affect the levels at the Fermi surface and of short-range correlations (SRC) that are mainly due to tensor interactions and lead to the depopulation of deep hole states. For non-closed-shell nuclei there is in addition particle core coupling leading to fragmentation of single-particle strength. Recent calculations including SRC in nuclear matter[1] report a substantial depletion ($\approx 20\%$) of deep hole states, which seems to be confirmed in electron scattering experiments.[2] Attempts to measure these occupation probabilities directly in transfer experiments on Pb are not yet conclusive.[3] On the other hand, dispersive potential studies for Pb and Ca discuss much smaller effects.[4]

In this Communication we present a detailed experimental study of the strength function in ^{41}Ca and compare with calculations including essential features in a realistic way. In the quasiparticle-phonon-coupling model the ground-state correlations in ^{40}Ca are treated in the pairing approximation while the fragmentation in ^{41}Ca is described by coupling to phonon states. Higher momentum components are introduced explicitly by major shell mixing.

The strength functions are obtained from the analysis of the ^{40}Ca$(\vec{d},p)$ reaction data, taken with the Munich quadrupole-three-dipole magnetic spectrograph and 20-MeV polarized deuterons. In spectra with 6-keV energy resolution at scattering angles ranging from 5° to 55°, more than 180 transitions in ^{41}Ca with excitation energies up to 8.7 MeV have been identified. To most of them orbital and total angular momentum l and j, respectively, have been assigned and spectroscopic factors $S_{lj}(E_x)$ were extracted on the basis of distorted-wave Born approximation (DWBA) and coupled-channels Born approximation (CCBA) analysis of angular distributions of cross section and vector-analyzing power as in Ref. 5.

In Fig. 1 typical results are displayed for transitions with orbital angular momentum transfer $0 \leq l \leq 4$ emphasizing transitions to higher excited states with small spectroscopic factors. The solid curves represent DWBA or CCBA calculations with the values of the transferred angular momenta indicated. The dashed curves show the alternate choice of $j = l \pm \frac{1}{2}$. The experimental features are reproduced by the calculations. For a unique determination it is essential to completely cover the the forward angular region. In calculations with the code CHUCK3 (Ref. 6) we used optical potentials from the literature.[7,8] The transfer form factors were calculated in the conventional well-depth procedure in a Woods-Saxon potential with fixed geometry ($r_0 = 1.2$ fm, $a = 0.65$ fm, $\lambda = 25$). Nonlocality and finite range corrections[9,10] have been included. Positive parity states in ^{41}Ca may be populated from ^{40}Ca by direct transfer or by two-step transfer in-

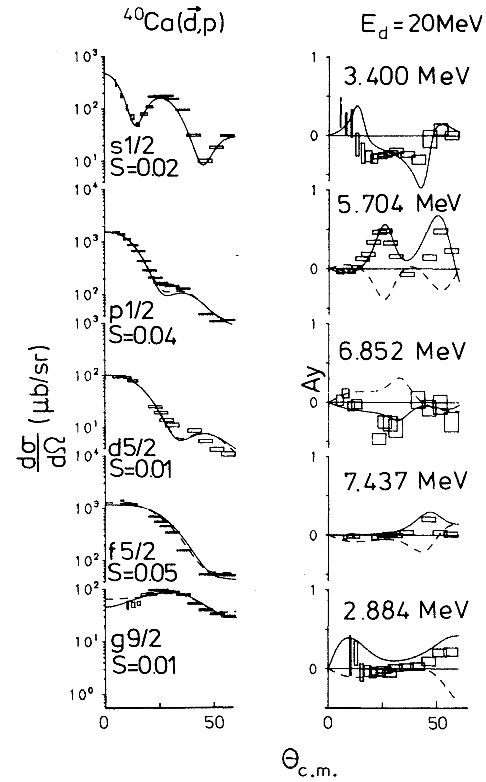

FIG. 1. Angular distributions of differential cross section $d\sigma/d\Omega$ and vector-analyzing power A_y. The rectangles represent the measured data with statistical error in the vertical direction and the actual value of the opening angle of the spectrograph in horizontal direction. The curves represent DWBA ($2p\frac{1}{2}$, $1d\frac{5}{2}$, $1f\frac{5}{2}$, $1g\frac{9}{2}$) or CCBA ($s\frac{1}{2}$) calculations (see text).

elastic processes, i.e., CCBA-type contributions. They have been estimated using the configuration $|1f\frac{7}{2}\times{}^{40}\mathrm{Ca}(3^-)\rangle j$, which is likely to give the most important contribution. The spectroscopic factors are only moderately changed[11] by including these two-step contributions except for some low-lying $\frac{5}{2}^+$ states.

Theoretical spectroscopic factors have been calculated in a quasiparticle-phonon-coupling model, applied successfully in the analysis of other (f,p) shell nuclei,[12,13] describing the states in ^{41}Ca as

$$|j^\pi,E_x\rangle=\sum_{n=1}^{4} z_{nlj}(E_x)\,|nlj^\pi\rangle+\sum_{j'}\sum_{J_c} z_{(j'J_c)j}(E_x)\,|(j'J_c)j^\pi\rangle\,. \qquad (1)$$

The first term is a superposition of one quasiparticle state with different radial quantum numbers n, the second couples quasiparticles j' to core excitations J_c.

Thus, normalized transfer form factors are given by

$$\Phi_{lj}(E_x,r)=\sum_n z_{nlj}(E_x)u_{nlj}\phi_{nlj}(r)/[S_{lj}(E_x)]^{1/2}\,, \qquad (2)$$

with spectroscopic factors

$$S_{lj}(E_x)=\sum_n |z_{nlj}(E_x)u_{nlj}|^2\,. \qquad (3)$$

The u_{nlj} are the BCS amplitudes. With a neutron pairing force parameter $G_n=23.5$ MeV/nucleon ($G_p=25.5$ MeV/nucleon for protons)[12,14] we obtain occupancies $v^2=1-u^2$ of 97.5%, 89%, and 5% for $(nlj)=2s\frac{1}{2}$, $1d\frac{3}{2}$, and $1f\frac{7}{2}$ neutron states in ^{40}Ca similar to Hartree-Fock-Bogoliubov (HFB) results in other closed-shell nuclei.[15] Additional correlations other than pairing as discussed in Refs. 1 and 16 would change these values.

The core excitations are described here by two quasiparticles random-phase approximation (QRPA) states. For convergence of the wave functions of better than 0.1% we had to include QRPA states up to $E_x\approx 20$ MeV and $J_c\leq 6^\pm$ and, even more important, to use a sufficiently large configuration space of neutron states up to $E_x\approx 18$ MeV. The single-particle states have been calculated in Woods-Saxon potentials fitted to Hartree-Fock results.[17] The continuum was made discrete. The residual interaction was derived from the M3Y-G-matrix but renormalized to the commonly used Landau-Migdal parameters.[18]

In Figs. 2(a) and 2(b) the empirical and theoretical spectroscopic strength distributions (solid and dashed lines, respectively) are compared as cumulative sums $\sum_n S_{lj}(E_n)$ for predominantly empty orbitals [Fig. 2(a)] and for predominantly filled orbitals [Fig. 2(b)]. The energy range extends to $E_x=8.7$ MeV, about 0.4 MeV above the neutron emission threshold.

Up to $E_x\approx 5$ MeV we identify all known states in ^{41}Ca.[19] At higher excitation energies the observed level density saturates. From the strength and angular distributions of the unresolved background, we conclude[11] that the summed empirical strengths in Figs. 2(a) and 2(b) correspond to at least 95% of the direct transition strength. In several cases the spins could not be determined safely from the analyzing powers because of either poor statistics or incomplete or structureless data. Then the lower curves represent the safe j assignments and the upper ones also include the tentatively assigned states.

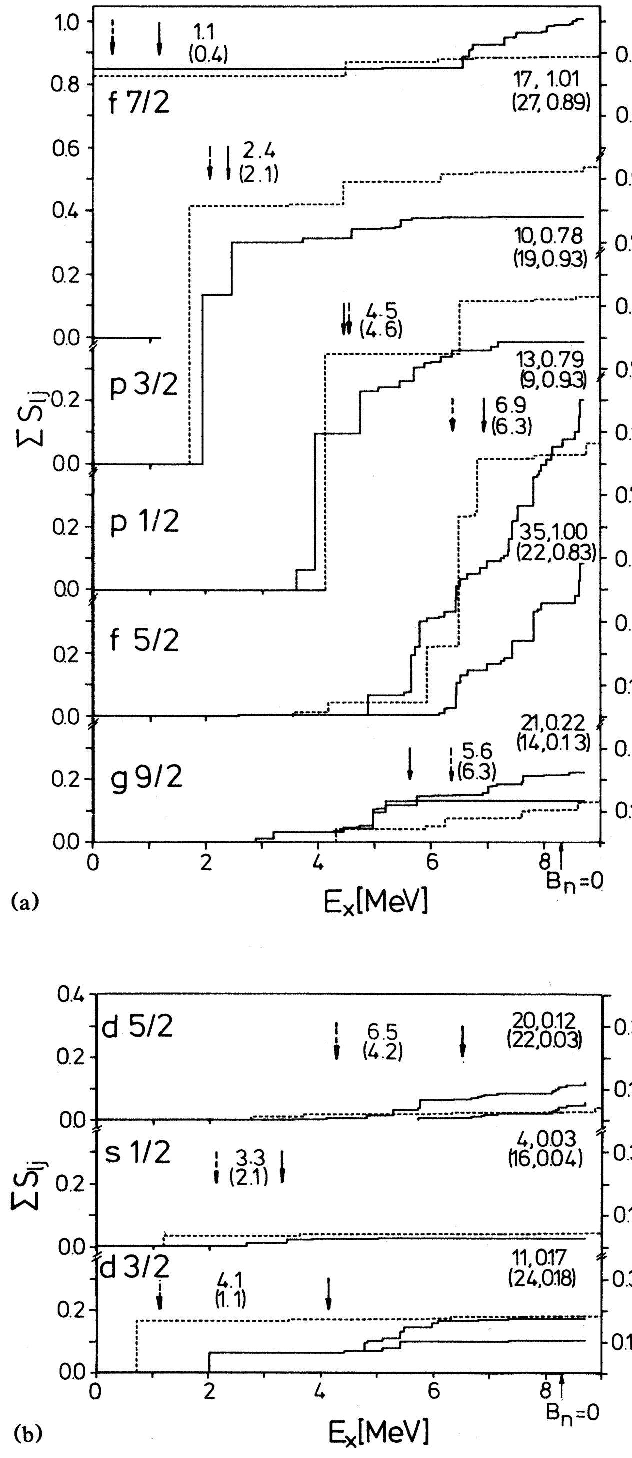

FIG. 2. Cumulative sum of spectroscopic factors $\sum_n S_{lj}$, summed for $E_n<E_x$, for particle-type orbitals in part (a) and hole-type orbitals in part (b). Compared are the results of the empirical analysis [solid curve, lower and upper curves for safe and all assignments (see text)] and the microscopic calculation (dashed curve). Also given are for the range $0\leq E_x\leq 8.7$ MeV the number of states, the summed strength and the centroid energies (theoretical values in parenthesis).

The observed summed strength for the $f\frac{7}{2}$, $p\frac{3}{2}$, and $p\frac{1}{2}$ orbitals are close to unity. For the first time (compare Refs. 4 and 19) a considerable fraction of $f\frac{5}{2}$ strength has been measured. The $g\frac{9}{2}$, $d\frac{3}{2}$, $s\frac{1}{2}$, and $d\frac{5}{2}$ orbitals are only weakly populated and strongly fragmented. The theory satisfactorily reproduces the average features of the experimental results. However, the calculation underestimates the degree of fragmentation which is probably due to the restriction to one and three quasiparticle configurations (giving, however, a large number of states with strengths below the experimental observability $S_{lj} \approx 10^{-3}$).

Discrepancies with respect to the absolute magnitude of spectroscopic factors can be understood in terms of differences between radial form factors from the empirical well depth prescription and the microscopic QRPA calculations [Eq. (2)]. This point is investigated by comparing rms radii. We found that the trend of the theoretical form factors, a general increase of the rms radii with increasing excitation energy, was reproduced by the well-depth method on the average, but deviations occur particularly for weak states and for those which are shifted strongly from the unperturbed single-particle energy.

For the $\frac{7}{2}^-$ ground state the microscopic and the empirical method give the identical rms radius $r=3.99$ fm which is, furthermore, in perfect agreement with a recent result from a magnetic electron scattering study on ^{41}Ca.[20] Our empirical spectroscopic factor $S=0.85$ agrees with the theoretical value $S=0.83$ and the electron scattering result 0.83 ± 0.05.[20] Thus, the method of our analysis and the structure calculations are confirmed in an essential aspect.

For the lowest $\frac{3}{2}^+$ state Pinkston, Philpott, and Satchler[21] analyzed (d,p) data in the source-term method and obtained $S\approx0.16$, which is close to our microscopic value of 0.17, while in the well-depth procedure we obtain $S=0.06$. However, the summed strength agrees well, indicating that state dependent effects average out in the summation of spectroscopic factors. This was also found by Bernhardt *et al.*[22] for a similar problem with $\frac{15}{2}^+$ states in ^{209}Pb.

For the $\frac{1}{2}^+$ states the microscopic form factors have rms radii systematically smaller than the ones used in the analysis. The experimental value for the summed strength of 0.03 might, therefore, increase by a factor up to 2.5.

For the $d\frac{5}{2}$ orbital the summed strength $\sum S=0.12$ exceeds the microscopic value of 0.03. However, the analysis assumes $1d\frac{5}{2}$, while microscopically a gradual shift from $1d\frac{5}{2}$ to $2d\frac{5}{2}$ occurs with increasing excitation energy. Using a pure $2d\frac{5}{2}$ form factor the strength would be reduced by a factor of about 2. The identification as predominantly $2d\frac{5}{2}$ strength is further supported by comparison with the $1g\frac{9}{2}$ orbital, having nearly the same single-particle energy and the strength located in the same energy range. We conclude, that $1d\frac{5}{2}$ strength of less than 0.05 is observed.

To summarize, the measured strength functions for the p, f, and g states are reproduced quite satisfactorily by the microscopic calculations. For the $1d\frac{3}{2}$, $2s\frac{1}{2}$, and $1d\frac{5}{2}$ orbitals in ^{40}Ca a depletion of 0.11, 0.025, and 0.013, respectively, was obtained with the BCS calculations. In a dispersion theoretical study Johnson and Mahaux[4] find for these states depletions of 0.11, 0.09, and 0.07. For deep hole states, down to $1s\frac{1}{2}$, they obtain depopulations of 0.06 to 0.03 being systematically larger than the BCS results. Since their approach is based on empirical optical potentials any kind of correlations are included effectively. These larger values can be attributed to SRC not accounted for in our calculations. The theoretical spectroscopic strength in addition is affected by core coupling and major shell mixing, resulting in an enhancement by factors of 1.6 to 2.3 for $E_x \leq 8.7$ MeV. The empirical values lie in between our core-coupling results and those of Ref. 4 and definitely rule out the large depletions discussed in Ref. 1.

This work was supported in part by the Bundeministerium für Forschung und Technologie.

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